TIARES Project—Tomographic investigation by seafloor array experiment for the Society hotspot

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We conducted geophysical observations on the French Polynesian seafloor in the Pacific Ocean from 2009 to 2010 to determine the mantle structure beneath the Society hotspot, which is a region of underlying volcanic activity responsible for forming the Society Islands. The network for Tomographic Investigation by seafloor ARray Experiment for the Society hotspot (TIARES, named after the most common flower in Tahiti) is composed of multi-sensor stations that include broadband ocean-bottom seismometers, ocean-bottom electro-magnetometers, and differential pressure gauges. The network is designed to obtain seismic and electrical conductivity structures of the mantle beneath the Society hotspot. In addition to providing data to study the mantle structure, the TIARES network recorded unprecedented data of pressure and electromagnetic (EM) signals by tsunamis associated with large earthquakes in the Pacific Ocean, including the 2010 Chilean earthquake (M_w 8.8).
Key words: Hotspot, mantle plume, tsunami, ocean-bottom seismograph, ocean-bottom electro-magnetometer.

1. Introduction

The French Polynesian region is characterized by positive topographic anomalies of 700 m, a concentration of hotspot chains, and a broadly-distributed low-velocity anomaly in the lower mantle revealed by seismic tomography (e.g., Garnero, 2000). These previous observations suggest the presence of a "superplume", which is a large-scale mantle flow rising from the bottom of the mantle beneath the region (e.g., Larson, 1991). We performed broadband ocean-bottom seismometer (BBOBS) observations over the entire French Polynesian region, from 2003 to 2005, to determine a large-scale seismic structure of the mantle (Suetsugu *et al.*, 2005). Our previous data revealed that large-scale low-velocity anomalies (on the order of 1000 km in diameter), indicative of the superplume, are located from the bottom of the mantle to a depth of 1000 km, and small-scale low-velocity anomalies (on the order of 100 km in diameter) are present above the superplume (Fig. 1, modified from Suetsugu *et al.*, 2009). The small-scale anomalies, possibly mantle plumes, are present beneath the Society and Macdonald hotspots, which agrees with the results obtained from early magnetotelluric tomography (Nolasco *et al.*, 1998). However, the explanation remained unclear because the insufficient station coverage impeded the investigation of the anomaly routes to the hotspots and their depth extents. If the hotspots are fed by the mantle plumes ascending from the lower mantle, a substantial mixing of materials may be occurring between the upper and lower mantle. The results may lead to a significant contribution in understanding the evolution of the Earth.

2. Seismic, Electromagnetic, and Pressure Observation on the Seafloor

We focused on the Society hotspot by deploying the TIARES network in its vicinity from 2009 to 2010. We installed nine pairs of BBOBSs and ocean-bottom electro-magnetometers (OBEMs) in February 2009 on the seafloor at a depth of 4000–5000 m aboard the research vessel MIRAI of the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) (Fig. 2). The recovery cruises were conducted in November–December 2010 aboard the Tahitian fishing boat Fetu Mana. The project was conducted as a Japan-France cooperative effort. The Japanese BBOBS and OBEM have been developed by the Earthquake Research Institute of the University of Tokyo since 1990 (Fig. 3). The BBOBS was equipped with a broadband sensor that can record ground motions at periods from 0.02 to 360 s, and the OBEM was equipped with a fluxgate magnetometer and two mutually-orthogonal pairs of electrodes that measure variations in three components of the magnetic field and two horizontal components of the electric field (Fig. 3). The differential pressure gauge (DPG) sensors were attached with the BBOBS at two stations (SOC2 and SOC8 in Fig. 2). All instruments were operational for 1.5 years. Refer to Shiobara *et al.* (2009) for details of the BBOBS and the OBEM, and Araki and Sugioka (2009)

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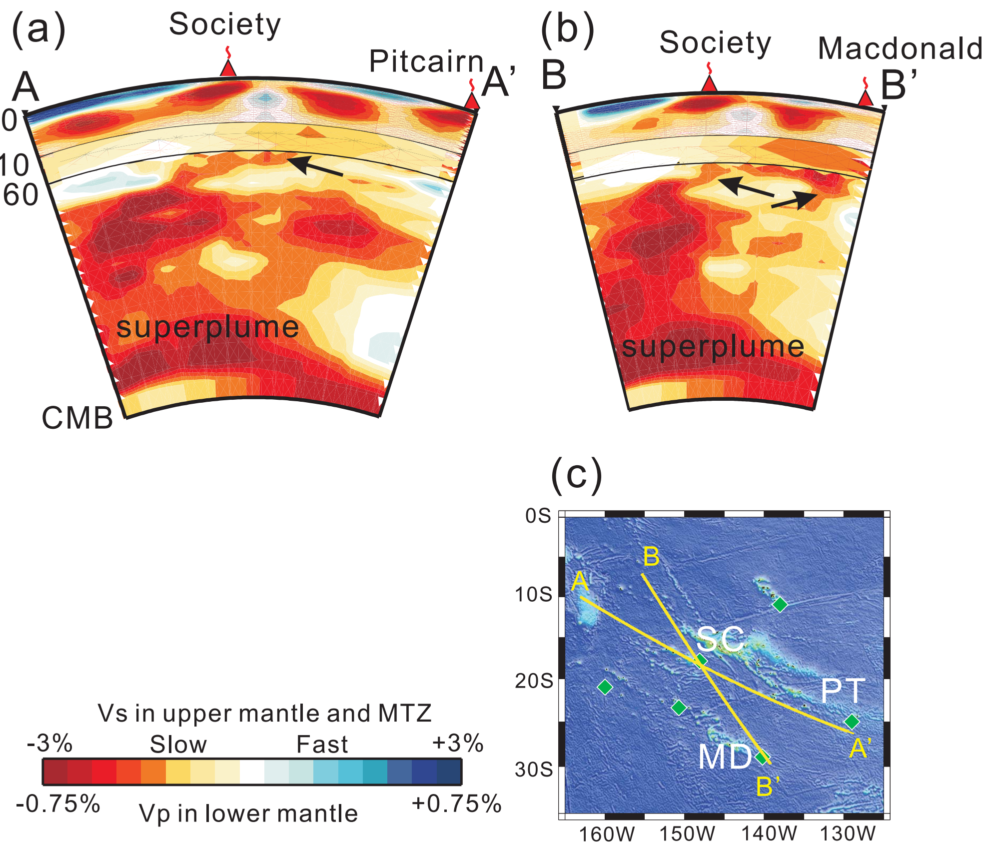

Fig. 1. Cross-sections of seismic structure in the entire mantle. S-wave velocities are shown for the upper mantle (0–410 km) and the MTZ (410–660 km). The model of Ritsema and van Heijst (2000) is shown for the MTZ structure. P-wave velocities are shown for the lower mantle (660–2900 km). Velocity scales are $\pm 3\%$ in the upper mantle and the MTZ and $\pm 0.75\%$ in the lower mantle. Green diamonds indicate hotspots in the Polynesian region. (a) Cross-section A–A′, passing the Society and Pitcairn hotspots; (b) cross-section B–B′, passing the Society and Macdonald hotspots. Narrow mantle plumes are indicated by arrows. (c) positions of the profiles. "SC," "PT," and "MD" in (c) indicate the Society, Pitcairn, and Macdonald hotspots, respectively. Modified from figure 11 of Suetsugu *et al.* (2009).

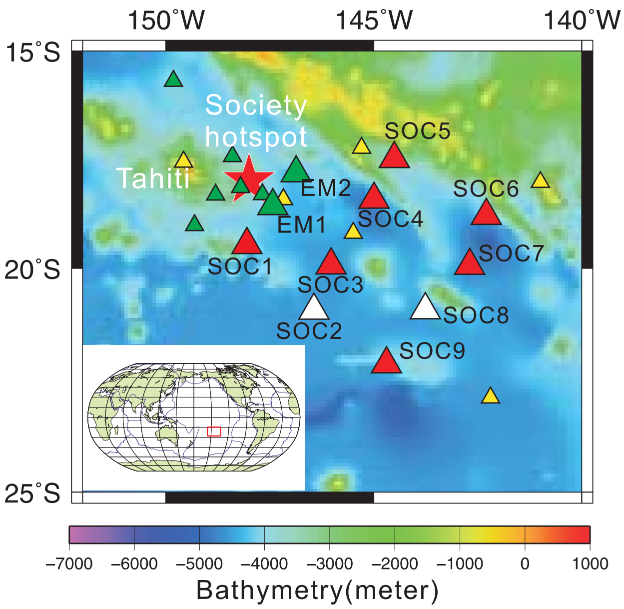

Fig. 2. TIARES stations (large triangles) on a bathymetric map. Open, red, and green triangles represent the stations equipped with BBOBS, OBEMs, and DPGs; BBOBS and OBEMs; and OBEMs, respectively. Other broadband seismic and electromagnetic stations are indicated by small yellow and green triangles, respectively. The red star indicates the Society hotspot.

for those of the DPG. The French team also installed two IUEM/INSU OBEMs (EM1 and EM2 in Fig. 2) that were used from 2009 to 2010 in the studied region. We designed the TIARES network configuration to determine a detailed structure beneath the Society hotspot down to the top of the lower mantle. This network observation is expected to reveal the mantle plumes which ascend from the lower mantle to the hotspot.

3. Planned Data Analyses

Figure 4 shows the noise spectra of the SOC1 records computed from 1.5-year-long data. The noise level on the vertical-component is well below that at high-noise land stations (Peterson, 1993) at periods longer than 10 s. This indicates that the vertical component of the BBOBS records are suitable for analyzing Rayleigh waves, which are sensitive to the upper mantle structure, and teleseismic P waves, which are sensitive to the deeper mantle structure; both types of waves have large long-period vertical motions. The noise level of the two horizontal components is lower than that at high-noise land stations at periods between a few seconds and 30 s, indicating that teleseismic S waves in this period range are useful. The horizontal noise level at periods longer than 30 s is comparable to, or greater than, that at high-noise land stations.

Hot mantle plumes should be detectable as low seismic

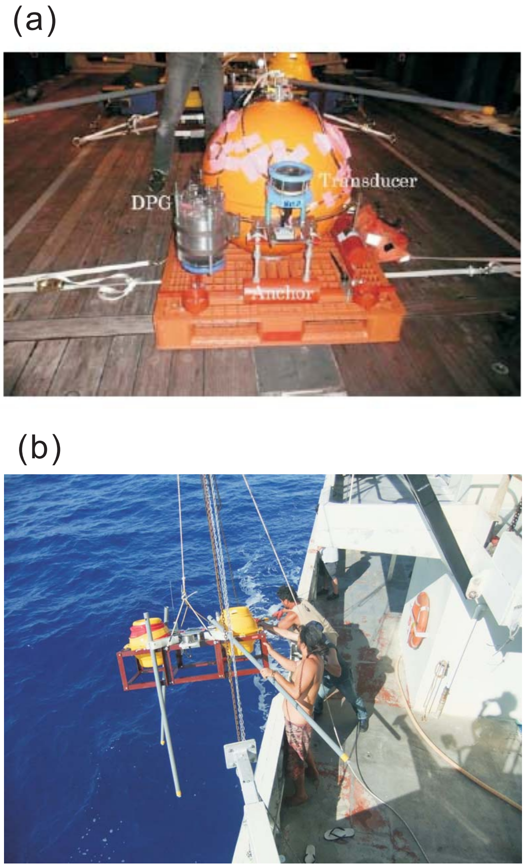

Fig. 3. (a) BBOBS on board R/V "MIRAI" just before installation. (b) OBEM recovered by the fishing boat "Fetu Mana."

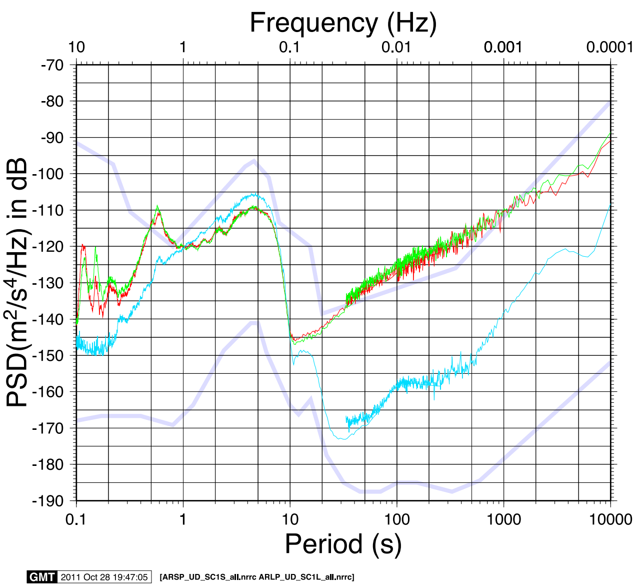

Fig. 4. The noise model of the SOC1 BBOBS station. The blue curve indicates vertical noise spectra. Green and red curves are noise spectra of the two horizontal components. Thick curves behind show the low- and high-noise models at land stations (Peterson, 1993).

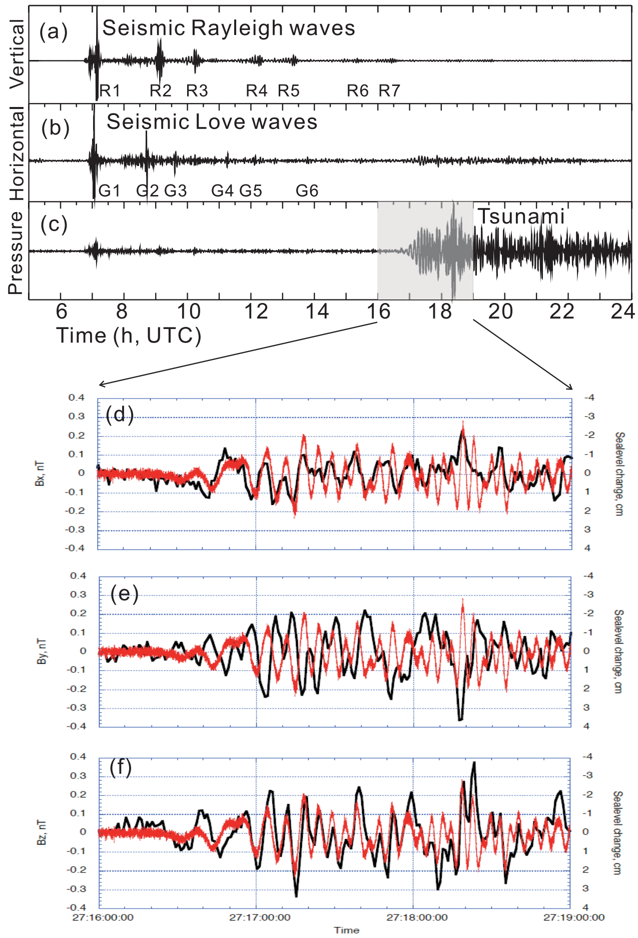

Fig. 5. 19 h records of (a) vertical component, (b) horizontal component, and (c) water pressure of the 2010 Chilean earthquake. R1, R2, ... and G1, G2, ... denote successive arrivals of Rayleigh and Love waves, respectively, which circled the Earth's surface. Bottom three panels: (d) EW component, (e) NS component, and (f) vertical component of 3-h geomagnetic records of the tsunami generated by the earthquake (black). The corresponding water pressure record (red) is superimposed.

velocity anomalies. Because of the low noise level of the vertical component of the BBOBS records, Rayleigh wave tomography should be the most effective method of detecting such velocity anomalies. Travel time tomography of teleseismic body waves will be employed to determine the seismic velocity structure in the mantle transition zone (MTZ), a depth range from 400 to 700 km, and the lower mantle. The topography of the mantle discontinuities (the 410-km and 660-km discontinuities) could be used as a "mantle thermometer" because they are interpreted as mineral phase changes controlled by temperature and pressure. Previous studies (e.g., Niu *et al.*, 2002; Suetsugu *et al.*, 2009) showed that the MTZ is thin (hot) beneath the Society hotspot. However, the spatial resolution of the previous results is poor because of the sparse data in the region. We will study the thermal structure in the MTZ by mapping the topography of the mantle discontinuities with considerably better spatial resolution by receiver function analysis (e.g., Owens and Crosson, 1988). This should help in determining whether the presumed mantle plumes ascend through the MTZ. The OBEM data will be analyzed with a three-dimensional magnetotelluric method (Tada *et al.*, 2011) to obtain the electrical conductivity structure down to the MTZ beneath the Society hotspot. Electrical conductivity is sensitive to temperature and composition (including the degree of mineral hydration) in a different manner from seismic velocities. Simultaneous use of BBOBSs and OBEMs could provide information on the elastic properties and electrical conductivities in the mantle, respectively, which would enable separate determination of the thermal and compositional characteristics of the mantle plumes (e.g., Fukao *et al.*, 2004).

4. Seismic and Tsunami Records of the 2010 Chilean Earthquake

During the observation period, the Chilean earthquake (M_w 8.8) occurred off the coast of Chile (35.846°S, 72.719°W) on February 27, 2010, which provided a unique opportunity to observe seismic waves and tsunamis triggered by the earthquake. Figures 5(a) and 5(b) show seismograms recorded for approximately one day at station SOC8, where BBOBSs, OBEMs, and DPGs were in operation. On the vertical and horizontal components, the surface waves circling the Earth several times were clearly observed. Approximately 10 h after the arrival of the first seismic wave, we observed a tsunami signal lasting for 5–6 h on the DPG sensor (Fig. 5(c)). Interestingly, we observed an electromagnetic (EM) signal simultaneously with the pressure signals, of which OBEM and DPG waveforms are similar (Figs. 5(d) and (f)), thus indicating that the EM signal was also caused by the Chilean tsunami. It is theoretically well understood that the movement of electrically-conductive ocean water in an ambient geomagnetic field induces secondary EM fields in the oceans (Sanford, 1971). However, until recent advances in high-precision measurement of the EM fields enabled the seafloor and island measurement of the tsunami signals (Manoj *et al.*, 2011; Toh *et al.*, 2011), this type of research was restricted by the low-signal tsunami EM levels. The EM measurement enables the evaluation of tsunami propagation direction and particle motion of the seawater, which could not be obtained from the pressure measurement. This is the first array observation of the EM field caused by a tsunami. We will be able to track the tsunami waves over eastern French Polynesia by analyzing the data from the TIARES network, which will enable the study of detailed tsunami propagation and its interaction with bathymetry.

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